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Collisionless Shocks and Mediating Instabilities

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A shock is characterised by a jump in several physical quantities, such as the particle density, the fluid velocity or the temperature. In contrast to hydrodynamic shocks, collisionless shocks form due to the interaction of particles with electromagnetic fields. Micro turbulence is seeded due to plasma instabilities, which is then transformed to a large scale structure. In different sub-projects, we have studied the shock formation process and the mediating instabilities in astrophysical environments. Furthermore, the findings are applied to the field of laser-plasma physics in order to benefit from an interdisciplinary approach.

1 Introduction

Collisionless shocks are important in various fields of physics. They have been most prominent in the context of space and astrophysics in order to explain the open problem of acceleration of cosmic rays to very high energies. Although having been studied for many decades, many open questions still remain regarding the formation process, the dissipation of energy and the particle acceleration process. In this context, mediating plasma instabilities play a key role. We outline below 5 sub-projects that take advantage of parallel simulations with high performance supercomputing resources in order to investigate either the formation and saturation of shocks, related shear flows and field amplification, or laboratory applications.

Electromagnetic shocks are triggered by the filamentation[1] or Weibel[2] instability. In anisotropic plasma flows electromagnetic fluctuations develop which can create a strong magnetic field. This leads to a deflection of charged particles and a mass accumulation that triggers the collisionless shock. The process of shock formation is investigated in a sub-project presented in Sec. 2. The large scale formation of the field is studied in a different project which is described in Sec. 3. While the above mentioned projects deal with an idealised system of symmetric flows, it is important to take into account less ideal conditions for understanding the realistic, non-ideal scenario. In a further sub-project, electromagnetic modes in shear flows are investigated and presented in Sec. 4.

In two further sub-projects we connect astrophysics with laser-plasma physics. In Sec. 5, a method is presented which allows us to mimic astrophysical scenarios in the laboratory, helping to understand the processes at stake in the universe. In the second project, the theory on shock physics is simulated under laboratory conditions for the generation of energetic ions with applications in inertial fusion or medical physics, see Sec. 6.

All simulations were performed with the fully relativistic particle-in-cell code OSIRIS[3,4].

2 Formation of Electromagnetic Shocks

A collisionless electromagnetic shock forms in an ideal setup of two symmetric, cold counterstreams with relativistic fluid velocities. We studied the formation of such shocks in electron-positron pair plasmas and electron-ion plasmas. It was found that the time to form a steady-state shock in pair plasmas takes two times the saturation time of the mediating plasma instability[5,6]. The formation process for electron-ion shocks was expected to scale similarly due to the rapid relativistic mass increase of the electrons, which happens on a few ω_{pe}^{-1}. A parameter scan of electron-ion shocks with different beam Lorentz factors and electron to ion mass ratios showed a formation time approximately 3 times longer than for pair shocks. After saturation of the filamentation instability on the ion time scale, an additional merging time of the magnetic field filaments is necessary, prolonging the shock formation process[7]. At the time of magnetic field saturation, the filament size is not big enough in order to significantly deflect the ions. Fig. 1 shows the paths of electrons and ions in the 2D simulation plane.

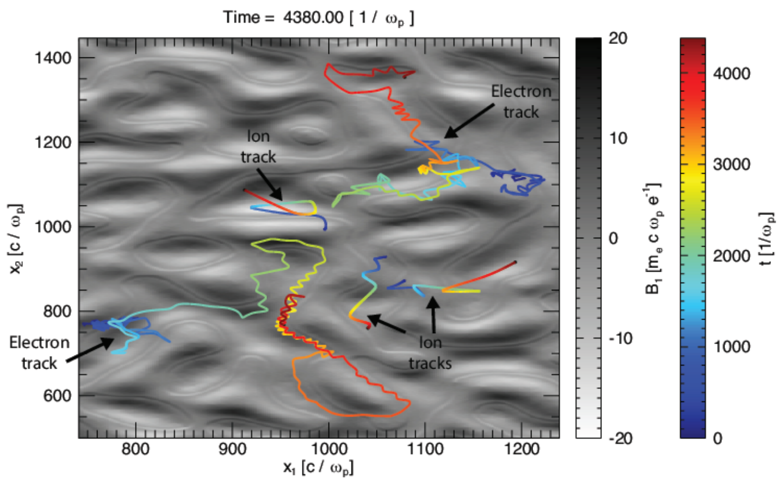

Figure 1. Magnetic field at $t = 4380\,\omega_{pe}^{-1}$ (gray) and particle tracks (colour).

3 Formation of Large-Scale Magnetic Fields

The origin of magnetic fields starting from unmagnetised plasmas is an important topic of modern research. Although much of the universe is magnetised (typically of order $10^{-6}G$) such that the magnetic field plays an important role in the dynamics, in the early universe this was not so. During the period of the cosmic microwave background, before recombination, it is widely accepted that there was no magnetic field[8]. Magnetic field growth is generally attributed to the turbulent dynamo[9,10], which amplifies a required initial seed field. The source of this initial seed has been speculated to come from the Biermann battery mechanism[11], or microinstabilities such as the Weibel[2] or filamentation instabilities[1].

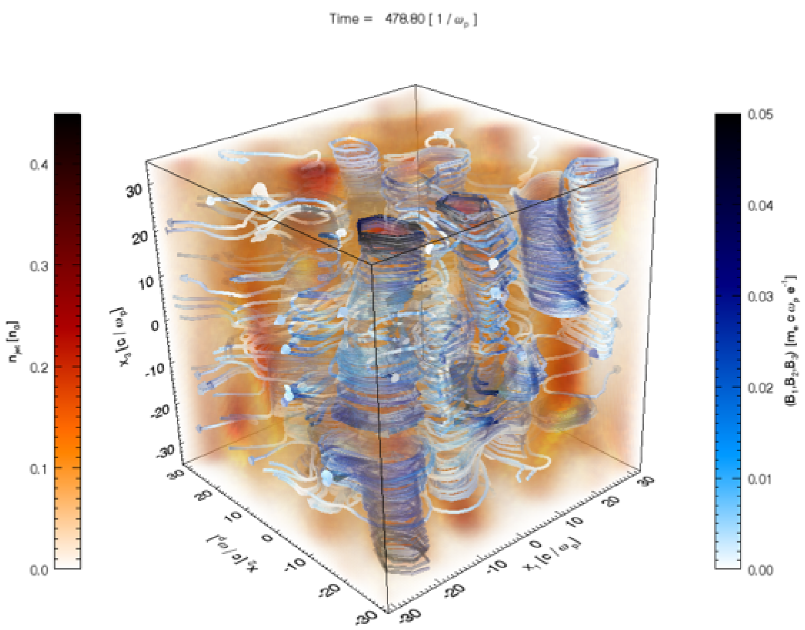

Figure 2. A still frame (at $t\omega_{pe} = 235.2$) from a movie showing the density of the fast moving jet of electrons, and a selection of magnetic field lines which surround the current filaments which have been formed at the electron inertial scale (kd_e) and begun merging to larger scales.

Fields generated by the Weibel instability have the advantage that the saturated fields reach magnetic pressures of the order of the plasma pressure ($\beta \equiv 8\pi P/B^2 \sim 1$) consistent with the $10^{-6}G$ fields seen today, and thus not much amplification is required. A big open question, however, is how these magnetic fields which form on very small spatial scales could change to the much longer observed scales. Besides the question of the origin of astrophysical magnetic fields, which vary over astrophysical length scales, this problem of scales has direct importance in the context of laser-solid experiments. In particular, experiments performed at the Tata Institute of Fundamental Research, Mumbai[12] show turbulent spectra of magnetic fields that reach scales far surpassing the microscopic scales of the Weiblel instability.

Using OSIRIS, we have performed 2D and 3D particle-in-cell simulations of the generation of magnetic field, due to the Weibel instability. We modelled a uniform plasma where a percentage of the electrons consist of a stream of electrons flowing near the speed of light, and the remainder flow backward to cancel the current. This setup approximates the hot electrons flowing into the target generated by the laser in the experiment. The stream of fast electrons breaks up into small current filaments (due to the Weibel/filamentation instability) with associated electron inertial scale magnetic fields (wavenumber, $kd_e \sim 1$), which merge in order to form larger scales (see Fig. 2). We can produce a distribution of k which can be compared with the experimental findings, for which we also find exciting

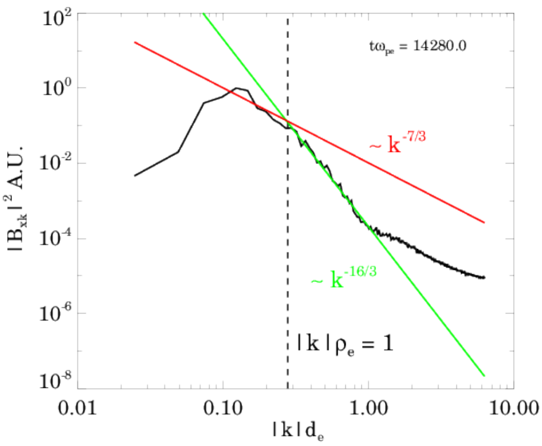

Figure 3. A plot of the magnetic field energy spectra at $t\omega_{pe} = 14280.0$, exhibiting two power law curves, $-7/3$ and $-16/3$, before and after the electron gyroradius scale ($k\rho_e$) respectively.

agreement with gyrokinetic power law predictions of the magnetic spectra[13] (see Fig. 3).

Although we find excellent agreement in the spectra at the scales simulated, we have measured the merging rate and concluded that it is too slow to explain the experimental results. Therefore effects such as coupling with larger scale features, and flow generated turbulence (which may be required for dynamo) must play an important role in explaining the large scale magnetic fields observed in the laboratory and in nature. These effects, which can only be captured in 3D, provide exciting future work that can be performed using more computationally intensive 3D particle-in-cell simulations.

4 Microphysics of Relativistic Collisionless Shear Flows

Relativistic collisionless shear flows are pervasive in some of the most extreme astrophysical scenarios such as gamma-ray bursts, active galactic nuclei and blazars. While the stability of such shear configurations have been studied at a macroscopic (magnetohydrodynamic) level, the role of microphysical (electron-scale) effects have been overlooked. In addition to providing dissipation on the micro-scale, the operation of microphysical processes and instabilities in shear scenarios can strongly modify the particle distributions (in space and momentum) of the plasma, impacting the long-term macroscopic evolution of such systems.

Using the particle-in-cell code OSIRIS[3] we have performed large-scale ($\sim 10^5$ core hours) multidimensional simulations of relativistic collisionless shearing plasma flows, and have identified a fast-growing electron-scale instability that leads to the development of mushroom-like structures in the electron-density, transverse to the flow direction; we have labelled this process the Mushroom instability (MI)[14]. Our numerical simulations have shown that the MI efficiently dissipates the immense kinetic energy available in relativistic shear flow scenarios, transforming it into electric and magnetic field energy, and

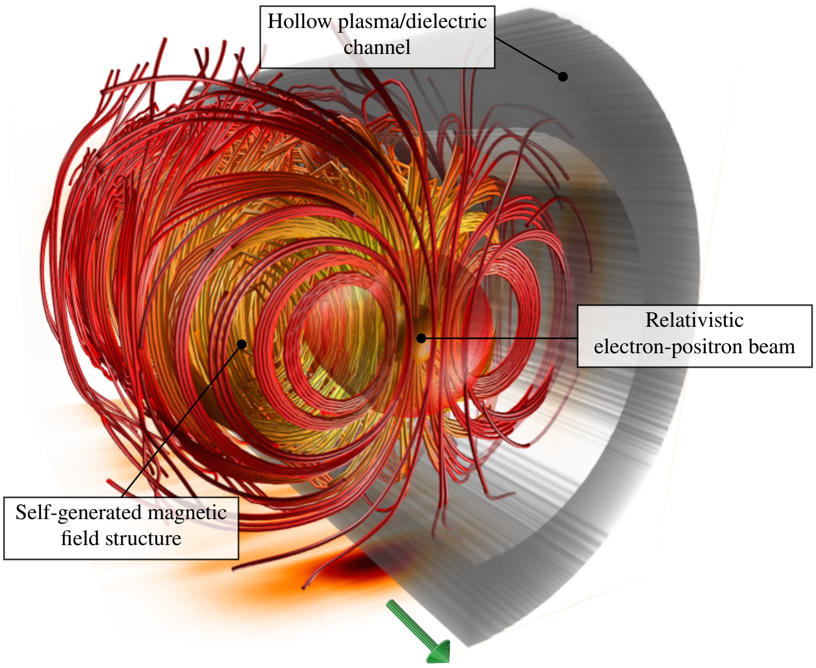

Figure 4. 3D PIC simulation of the interaction between a relativistic, globally neutral e^-e^+ beam (red/orange isosurfaces) and a hollow plasma channel (grey isosurfaces) whose inner diameter is $4\times$ wider than the transverse waist of the beam, to guarantee weak overlap (no contact) between the two; half of the cylindrical structure has been omitted to more clearly illustrate the dynamics of the beam inside. The e^-e^+ beam propagates in the positive x direction. The red lines represent the structure of the MI-generated magnetic field.

nonthermal acceleration of particles and radiation.

In an attempt to identify a laboratory configuration where the development of the MI can be verified, we have explored the dynamics of a relativistic, globally neutral electron-positron (e^-e^+) beam propagating through a hollow plasma channel. We have performed large-scale 3D PIC simulations ($\sim 10^5$ core hours) to investigate the propagation of relativistic e^-e^+ beams (with characteristics that are currently available at SLAC National Accelerator Laboratory) in hollow plasma channels with different diameters, and we have identified the development of the MI even in the absence of overlap (no contact) between the beam and the walls of the hollow channel (Fig. 4)[15]. We believe that this configuration reproduces the relativistic collisionless shear flow conditions that are relevant to extreme astrophysical shear scenarios, such as the shear interaction between relativistic astrophysical jets and the interstellar medium.

5 Brillouin Amplification: Towards Next Generation Laser Energy Densities

High-intensity lasers beams allow for the creation of high-energy-density (HED) conditions, that mimic extreme astrophysical scenarios, in controlled laboratory settings. These

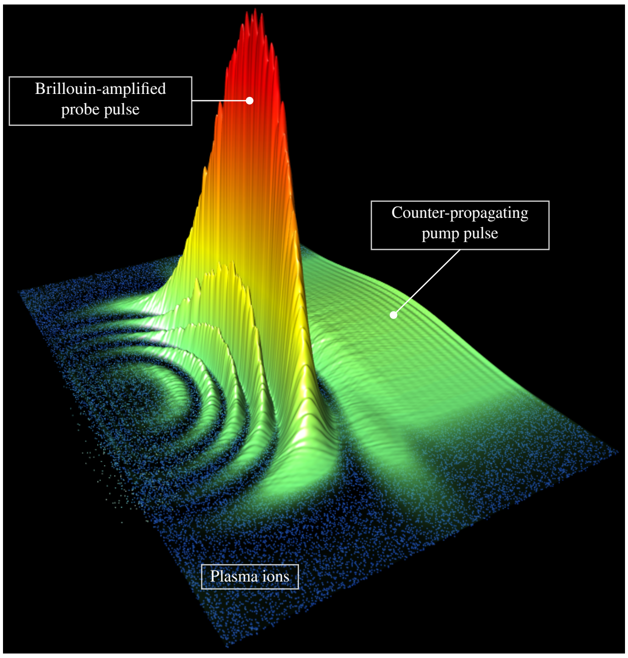

Figure 5. PIC simulation of successful Brillouin amplification. Contour surfaces represent the intensity envelopes of the counter propagating laser pulses, and the spheres represent the plasma ions that oscillate in the ion-acoustic wave. Initial pump and probe intensities are both 10^{16} W/cm^2 and the plasma density is 30% critical. It is shown that the probe pulse efficiently picks up the pump laser energy, reaching a peak intensity of 1.5×10^{17} W/cm^2 (15x the pump intensity) while preserving a smooth envelope. Transverse modulations in the probe envelope are observed due to the ponderomotive filamentation instability, but these still remain at a tolerable level at this stage.

exciting experiments give us a closer look at complex astrophysical processes that would otherwise have to be inferred indirectly by their radiation collected by our telescopes. Advances in the generation of higher laser powers and intensities is highly desirable, since these will give access to novel astrophysical conditions and exotic physical regimes of HED science, such as “boiling the vacuum”.

Further increasing current state-of-the-art laser energy densities is highly expensive using solid state optics. Plasma-based laser amplifiers, leveraging on parametric processes like stimulated Brillouin backscattering, overcome the optical damage limitations of solid state optics by several orders of magnitude, providing a promising alternative to the production of next generation laser energy densities.

We have performed large-scale ($\sim 10^6$ core hours), multidimensional PIC simulations in order to understand the main limiting parasitic instabilities (ponderomotive filamentation and Raman scattering instabilities) for Brillouin amplification over a wide range of parameters, including different plasma densities and laser intensities. With the aid of the large-scale PIC simulations and analytic theory, we have identified the optimal parameter regime where parasitic effects are minimised, allowing for efficient Brillouin amplification (Fig. 5). Our work is critical for the design of future Brillouin amplification experiments.

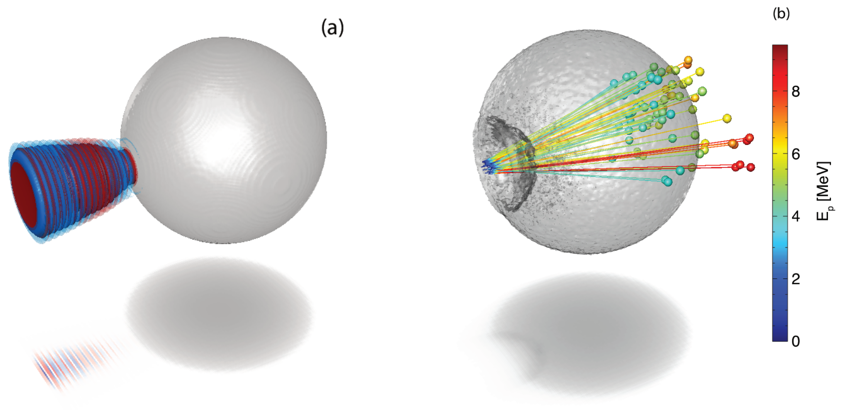

Figure 6. (a) Initial setup of the experiment: a frozen hydrogen pellet is irradiated by a laser. (b) Ions are accelerated through the target.

6 Generation of Energetic Ions with Collisionless Shocks

There are many applications which require energetic ions, e. g. for plasma diagnostics, fusion or medical physics. This acceleration can be efficiently done by irradiating a plasma with a laser. Depending on the actual target setup, different acceleration mechanisms can dominate. With 3D particle-in-cell simulations, we studied the parameter conditions for shock acceleration, which is very efficient in terms of final energy output[16]. Fig. 6a shows the setup of the experimental configuration: a frozen hydrogen pellet is irradiated by two laser pulses. The first pulse reduces the target density due to target expansion and the second pulse initiates the acceleration process. On the one hand, the laser has to be well focused in order to guarantee a high laser potential at the target surface, while on the other hand, a wide laser beam would be beneficial for producing a plane shock for a focused ion beam. The transport of the ions from the target surface through the target is shown in Fig. 6b, where only the paths of the most energetic ions have been selected. The density accumulation due to the laser and with the shock ahead (further inside the target), can be observed as well.

7 Concluding Remarks

The global topic of our research project is the investigation of collisionless shock formation. In this context, the mediating plasma micro-instabilities play a key role. We presented five sub-projects in which we have investigated the shock formation process, the evolution of electromagnetic instabilities on different scales, related shear flows and their applications in the laboratory. High performance supercomputing resources are absolutely necessary in order to understand the full physical picture. It is possible to analyse very small spatial scales with a high temporal resolution and to follow the evolution of nonlinear processes on long time scales. Furthermore, idealised setups allow to simplify the physics and to identify separate and basic processes.

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